The Lakes of Maple Valley and Covington

Water Quality Monitoring Results for Water Year 2016 at Lake Lucerne, Pipe Lake, and Lake Wilderness

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King County

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Water Quality Monitoring Results for Water Year 2016 at Lake Lucerne, Pipe Lake, and Lake Wilderness

Prepared for:

The Cities of Covington and Maple Valley

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King County Water and Land Resources Division
Department of Natural Resources and Parks

The King County Lake Stewardship Program

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Citation

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Table of Contents

Figures

Tables

EXECUTIVE SUMMARY

The King County Lake Stewardship Program works with resident volunteers to monitor water quality and lake use, and also to maintain residents' interest in lake health. Lake Lucerne, Pipe Lake, and Lake Wilderness have been monitored for decades. Beginning in 2005, monitoring of these three lakes has been funded by agreements between King County and the cities of Maple Valley and Covington.

Volunteer stewards monitored Lake Wilderness year-round in 2015 and 2016, taking daily measurements of precipitation and lake level and weekly measurements of water temperature and Secchi depth (water clarity). Twice a month during May-October 2015 and 2016, volunteer stewards at all three lakes also collected water samples at 1 m depth for biological and chemical analyses (e.g. chlorophyll, nitrogen, phosphorus). In May and August, additional measurements and samples were collected at mid-depth and 1 m above the lake bottom. These lake profiles help characterize conditions throughout the water column when the lake is thermally stratified.

Lake Lucerne and Pipe Lake continued to be categorized as oligotrophic, with moderately low algal productivity and good water quality. Lake Wilderness was categorized as mesotrophic, with higher algal productivity.

Average nitrogen to phosphorus (N:P) ratios were generally higher than 25 in Lake Lucerne, indicating that algal productivity was usually limited by phosphorus. The combination of low nutrient concentrations and phosphorus limitation created conditions that were unfavorable for cyanobacteria blooms. In Pipe Lake and Lake Wilderness, N:P ratios were below 25 for part of the sampling season, indicating that algal productivity may have been co-limited by both nitrogen and phosphorus. These nutrient conditions were more favorable for cyanobacteria to dominate the algal community.

Trend analyses of the long-term monitoring data found an increasing trend in the N:P ratio in Lake Wilderness, driven by both a decrease in total phosphorus concentrations as well as an increase in total nitrogen concentrations. The long-term data show that Pipe Lake water temperatures have been warming, with an average increase of 1.3°C per decade.

The monitoring conducted by volunteer stewards at these three lakes has built an invaluable long-term dataset for understanding water quality and lake health over time. Continued monitoring will help grow this dataset, increasing our understanding of how the lake reacts to environmental variability and human influences. The long-term dataset makes it possible to conduct statistically robust tests for trends, as well as to detect any potentially detrimental changes that may occur in the lake. In addition, long-term monitoring provides a solid scientific basis to guide lake management decisions by identifying emergent management needs and evaluating the effectiveness of management actions.

1.0 PROGRAM OVERVIEW

The Lake Stewardship Program has been working with dedicated resident volunteers to monitor Lake Lucerne, Pipe Lake, and Lake Wilderness for over 30 years. Both Lake Lucerne and Lake Wilderness are located entirely within the city limits of Maple Valley. Approximately 55% of the shoreline of Pipe Lake is in Maple Valley; the remainder is in Covington.

Specific objectives of the Lake Stewardship Program include: (1) gathering baseline data to assess long-term trends; (2) defining seasonal and water-column variability; (3) identifying potential concerns, and proposing possible management solutions when feasible; (4) educating lake residents, lake users, and policy makers about lake water quality; and (5) understanding the nature and character of the smaller lakes in King County.

At Lake Lucerne, a small number of samples were taken in the 1970s; consistent monitoring began in the 1980s and has continued since then with only one data gap in the early 1990s. Volunteer monitoring also began at Pipe Lake in the 1970s, and has been continuous since the early 1990s. Monitoring began at Lake Wilderness in the mid-1970s, and has continued with few gaps in the record. Beginning in 2005, the cities of Maple Valley and Covington established an agreement with King County to continue the volunteer monitoring program.

Lake Wilderness was monitored year-round (Level I monitoring) to observe the hydrological balance between the lake and its watershed, as well as to characterize lake level fluctuations throughout the entire year. Volunteers measured lake level and precipitation data each day at lake-side docks. They also made weekly measurements of water temperature and Secchi depth at a mid-lake sampling station. Level I data were reported to King County each quarter, quality-checked, and uploaded to the Small Lakes Data and Information webpage (http://green2.kingcounty.gov/SmallLakes).

From May through October, all three lakes received twice-monthly monitoring and water sampling (Level II monitoring) to measure nutrient and algal concentrations. At the mid-lake sampling station, volunteers also collected water samples from 1 m depth for chlorophyll, nutrients, and other chemical analyses. These water samples were picked up by Lake Stewardship staff and delivered to the King County Environmental Laboratory. Data were analyzed and uploaded to the Small Lakes Data and Information webpage

Both Level I and Level II volunteers routinely recorded their observations of recreational lake use, algal blooms, and weather conditions that may have had an effect on measurements. Volunteers were provided with training, equipment, and ongoing technical assistance. They were also invited to attend the annual Lake Stewardship Program training workshops held each year in late April.

2.0 WHAT WE MEASURE AND WHY

2.1 Types of Monitoring

Level I monitoring measures a few key parameters year-round. **Precipitation** and **lake level** are measured daily at lake-side docks. **Water temperature** (at 1 m depth) and **Secchi depth** are measured weekly at a mid-lake sampling station located over the deepest part of the lake. These year-round measurements are graphed by water year (October 1st through September 30th), rather than by calendar year.

Level II monitoring is conducted twice-monthly from May through October, at a mid-lake sampling station located over the deepest part of the lake. In addition to **water temperature** (at 1 m depth) and **Secchi depth**, water samples are also collected from 1 m depth and analyzed for:

- **Chlorophyll-*a***
- **Pheophytin**
- **Total nitrogen**
- **Total phosphorus**

Twice a year, in May and August, Level II monitoring includes a **water column profile** that collects temperature measurements and water samples from 1 m depth, mid-column, and 1 m above the lake bottom. These samples are analyzed for the usual Level II parameters plus:

- Inorganic nitrogen, as **ammonia** (NH_3) and **nitrate/nitrite** (NO_2/NO_3)
- Inorganic phosphorus, as **orthophosphate** (OPO_4)
- **Alkalinity**
- **Water color** (UV254)

2.2 Parameters

Physical parameters

Precipitation and **lake level** help us understand a lake's hydrological balance and track seasonal trends and long-term changes. Relationships between precipitation and lake level reflect watershed characteristics and groundwater inputs. Precipitation is measured with a plastic volumetric rain gauge mounted in an open area. Lake level is measured using a staff plate mounted to a fixed structure such as a dock.

Secchi depth is a measure of water clarity or transparency. A 20-cm (8-in) black-and-white Secchi disk is lowered into the lake until it disappears from view. Secchi depth is shallower when there are more suspended particles, such as sediment or algae, in the lake,.

Water temperature can affect the growth rates of plants and algae. In addition, cooler or warmer water temperatures favor different species of fish and other aquatic organisms. Temperature measurements in a water column profile also show the extent of lake stratification. In a stratified lake, surface waters are warmer than deeper, cooler waters, which reduces mixing between the two layers.

Nutrients

Phosphorus and **nitrogen** are naturally occurring elements necessary for growth and reproduction in both plants and animals. Fertilizer, pet waste, wastewater, and other human activities can increase the concentration of these nutrients in a lake. In lakes of the Puget Sound lowlands, biological productivity is most often limited by the amount of available phosphorus in the water. Increases in phosphorus can lead to more frequent and dense algae blooms – a nuisance to residents and lake users, and a potential health threat if blooms become dominated by cyanobacteria (blue-green algae) that can produce toxins.

The **ratio of total nitrogen to total phosphorus (N:P)** indicates whether nutrient conditions may favor the growth of cyanobacteria (blue-green algae). When N:P ratios are near or below 25, nitrogen is as likely to be the limiting nutrient as phosphorus. Certain cyanobacteria species can "fix" nitrogen (convert inert atmospheric N_2 into ammonia, which is biologically available), which gives them a competitive advantage over other algae when nitrogen is limiting.

Nutrients in a lake can be part of either organic or inorganic molecules. Inorganic forms of nitrogen are **ammonia** (NH_3) and **nitrate/nitrite** (NO_2/NO_3); the inorganic form of phosphorus is **orthophosphate** (PO_4). In deeper waters when dissolved oxygen concentrations are low, nutrients are found primarily in inorganic forms.

Algal pigments

Chlorophyll-*a* concentration is an indicator of the abundance of phytoplankton (algae) in a lake. Chlorophyll-*a* is a pigment necessary for algae to photosynthesize and store energy. While all algal cells contain some chlorophyll-*a*, the amount varies depending on the species. For example, some cyanobacteria have other light-catching pigments, and little chlorophyll-*a* compared to other algal types (e.g., diatoms and chlorophytes), so chlorophyll-*a* concentrations may not always correlate with the abundance of cyanobacteria.

Pheophytin is a product of chlorophyll decomposition and is generally measured along with chlorophyll-*a* as an indicator of how fresh or viable the phytoplankton in the sample are. Bottom sediments will contain a large amounts of pheophytin compared to chlorophyll-*a*, while actively-growing algae from the water column will have very little pheophytin present.

Other parameters

Microcystin and **anatoxin-*a*** are toxins produced by some species of cyanobacteria (blue-green algae). Microcystin is a liver toxin, and anatoxin-*a* is a neurotoxin. These toxins can cause illnesses in people and animals, with symptoms such as nausea and vomiting or numbness and tingling. High concentrations of cyanobacterial toxins are potentially lethal.

Alkalinity measures the buffering capacity of a lake, or the ability to resist changes in pH.

Water color is an index of the concentration of dissolved organic compounds in the water. It is measured as the absorbance of a specific wavelength of light (ultraviolet light at 254 nm) that is absorbed by many dissolved organic compounds.

Trophic State Index

The **Trophic State Index (TSI)**, developed and first presented by Robert Carlson in 1977, is a common index of a lake's biological productivity. TSI values are scaled between 0 and 100, which allows comparisons of water quality over time and among lakes.

- Lakes with TSI below 40 are classified as *oligotrophic*, or low-productivity, lakes. These lakes have low nutrient concentrations and little algal growth.
- Lakes with TSI between 40 and 50 are classified as *mesotrophic*, or moderate-productivity, lakes. These have moderate nutrient concentrations and moderate algal growth.
- Lakes with TSI above 50 are classified as *eutrophic*, or high-productivity, lakes. These lakes have high nutrient concentrations and high algal growth.

A lake may fall into any of these categories naturally, depending on conditions in the watershed, climate, vegetation, rock and soil types, as well as the shape and volume of the lake basin. Human activities such as land development, wastewater, and agricultural practices can also increase productivity, which is known as "cultural eutrophication."

TSI values are calculated using three related parameters: water clarity (Secchi depth), total phosphorus, and chlorophyll-*a.* The index assumes that higher phosphorus availability drives more algal production (and hence more chlorophyll-*a*), and more algal particles in the water decrease water clarity, and vice versa. Each parameter is used to calculate an independent estimate of the TSI.

If lake processes follow the assumptions of the index, the three TSI estimates are very close together. Substantial divergence among the TSI estimates warrants further investigation. Divergence may be due to data errors, or to special conditions in the lake that alter the usual relationships among nutrients, chlorophyll, and water clarity. For example, high concentrations of humic compounds will cause a dark water color that also reduces water clarity, independent of algal productivity.

Long-term trends

To test for long-term trends in the monitoring data, we fit a linear regression through annual average values (either year-round or May-October, depending on the parameter). Statistically discernable trends (slope $p<0.05$) are shown on graphs and described in the text.

3.0 LAKE LUCERNE RESULTS

3.1 Data Summary

Table 2 summarizes data from 2016, giving the minimum, mean (average) and maximum values measured for each parameter for the May-October sampling season.

Table 2. Lake Lucerne May-October summary statistics.

	Parameter	Minimum	Mean	Maximum
2016 May-Oct.	Secchi depth	3.8	4.9	5.5
	Temperature	13.0	19.2	23.0
	Chlorophyll-*a*	1.2	2.0	3.7
	Total Nitrogen	291.0	334.2	411.0
	Total Phosphorus	8.3	10.6	12.8
	N:P ratio	25.8	32.2	48.6

Note: Secchi depth in m. Temperature in degrees Celsius. Chlorophyll-*a*, pheophytin, total nitrogen, and total phosphorus in µg/L.

3.2 Secchi Depth

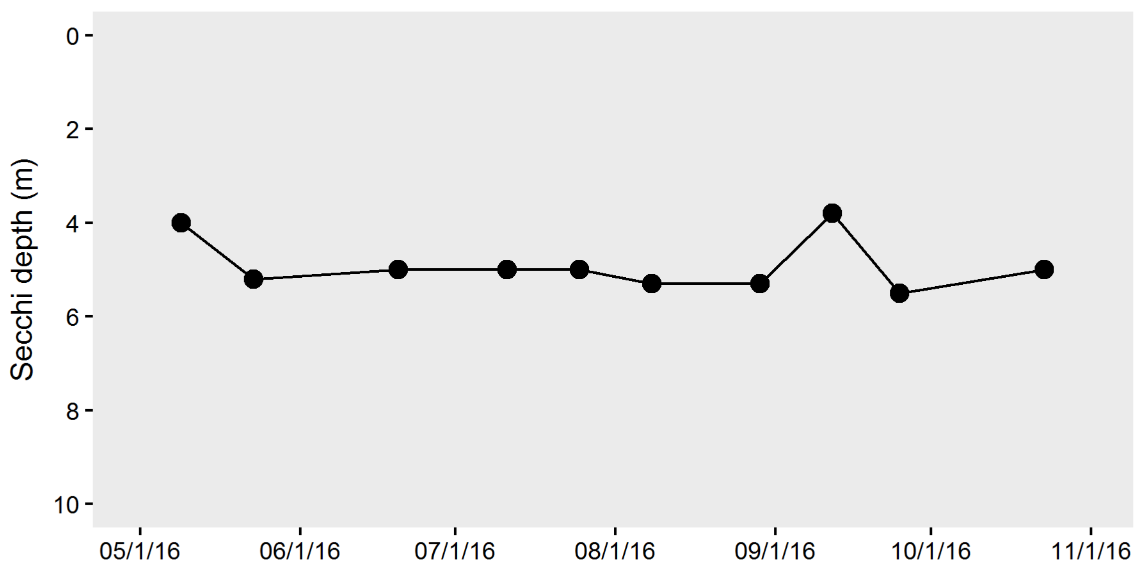

Figure 1. Lake Lucerne Secchi depth. Note the inverted Y-axis.

Lake Lucerne had fairly deep Secchi readings (high water clarity) compared to most small lakes in the region in 2016. Secch depth showed little variation throughout the sampling period, except for a relatively shallow reading on 9/12/2016.

3.3 Water Temperature

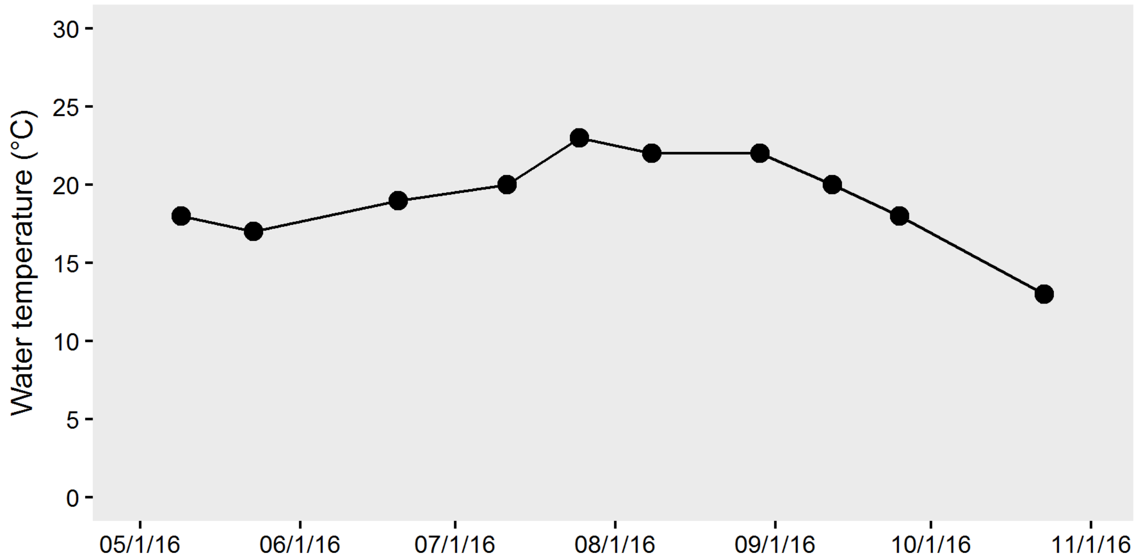

Figure 2. Lake Lucerne water temperature at 1 m.

Lake temperatures in 2016 followed a typical pattern for small lakes in the region, with temperatures warming through the spring, reaching a summer maximum, and cooling by late September.

Average May-October water temperatures in 2016 were lower than the previous few years. Overall, there is no increasing or decreasing trend in the long-term monitoring data.

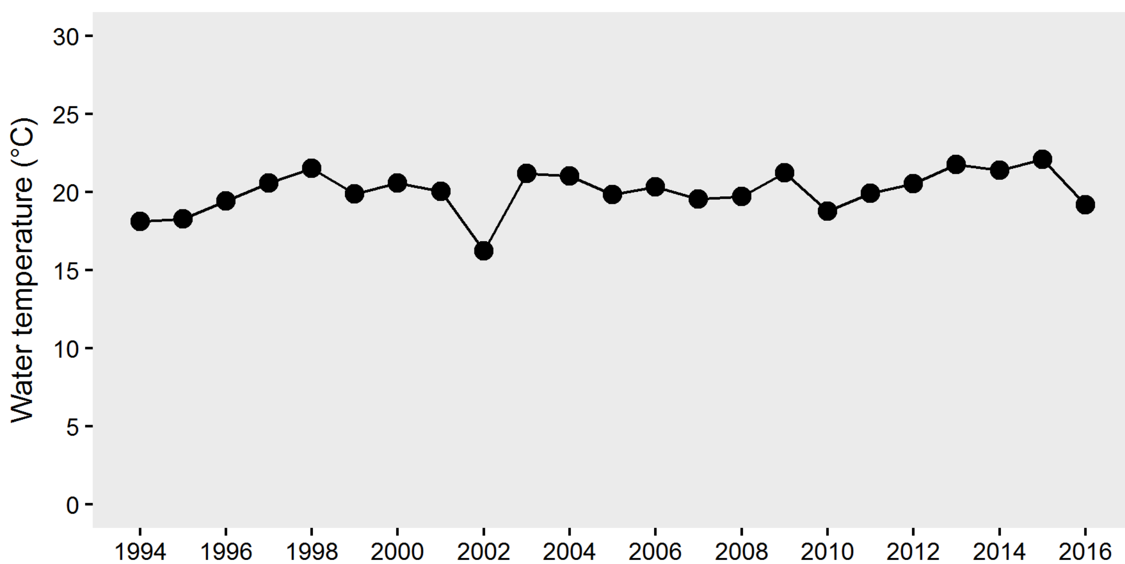

Figure 3. Lake Lucerne average May-October water temperature at 1 m.

3.4 Total Phosphorus and Total Nitrogen

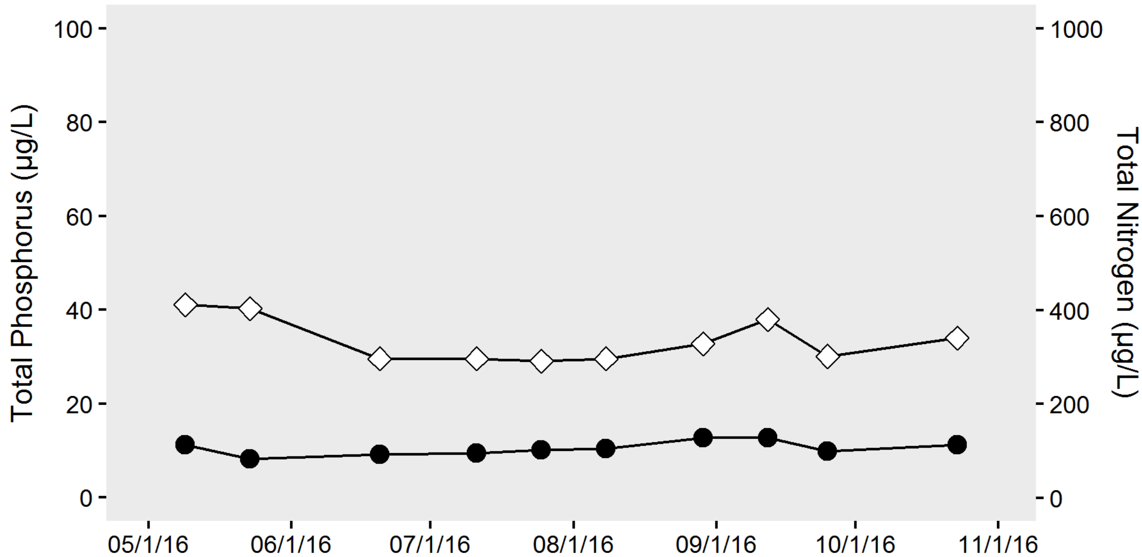

Figure 4. Lake Lucerne total phosphorus (black circles) and total nitrogen (white diamonds) concentrations in µg/L.

Nutrient concentrations remained fairly stable throughout the May-October sampling period. Total nitrogen had a small peak on 9/12/2016, on the same date as the shallower Secchi depth. However, there was no corresponding increase in chlorophyll-*a* concentrations on that date, which we would have expected if the higher nitrogen had caused an increase in algal biomass. The 9/12/2016 higher total nitrogen and shallower Secchi depth were likely coincidental, not causally related.

3.5 Nutrient Ratios

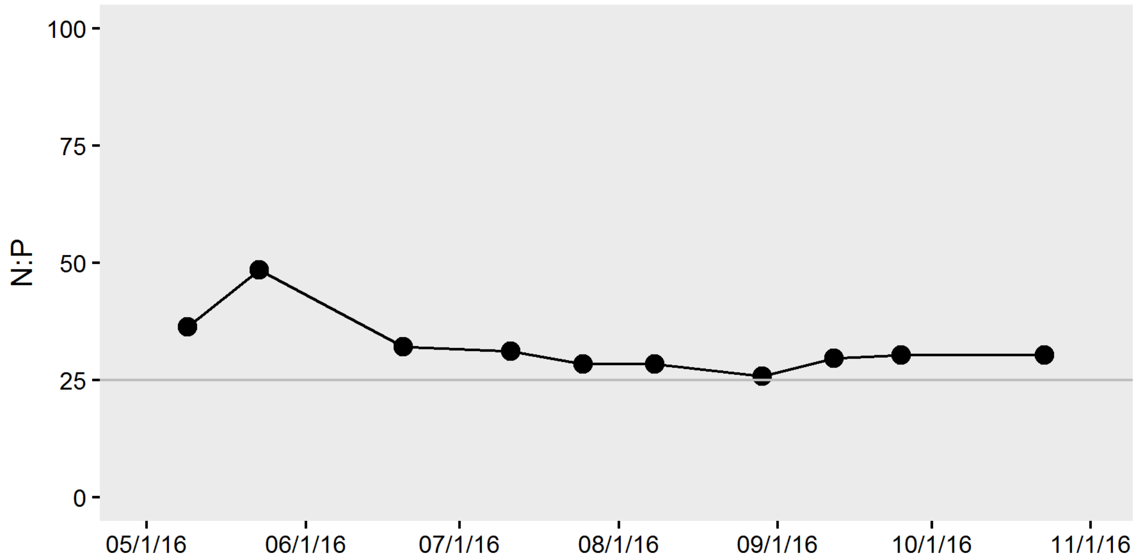

Figure 5. Lake Lucerne N:P ratios. N:P ratios at or below 25 (solid line) indicate possible nitrogen limitation.

The ratio of total nitrogen to total phosphorus (N:P ratio) in Lake Lucerne declined from spring through late summer. This reflects the fact that total nitrogen was declining during that time, while total phosphorus was increasing slightly. The N:P was above 25 throughout 2016. While phosphorus was most likely the limiting nutrient in the lake, summertime N:P ratios close to 25 indicated possible co-limitation by both nitrogen and phosphorus during that period.

The 2016 average N:P ratio was the lowest of any year on record for Lake Lucerne. Long-term monitoring data suggest that this is due to year-to-year variability, rather than an overall trend.

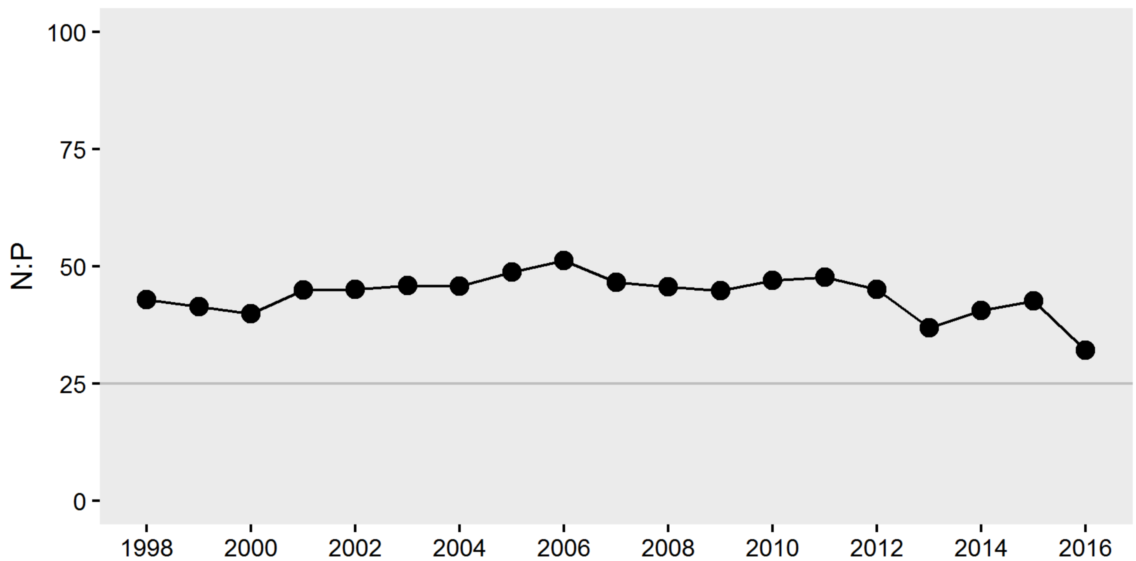

Figure 6. Lake Lucerne average May-October N:P ratios.

3.6 Chlorophyll-*a*

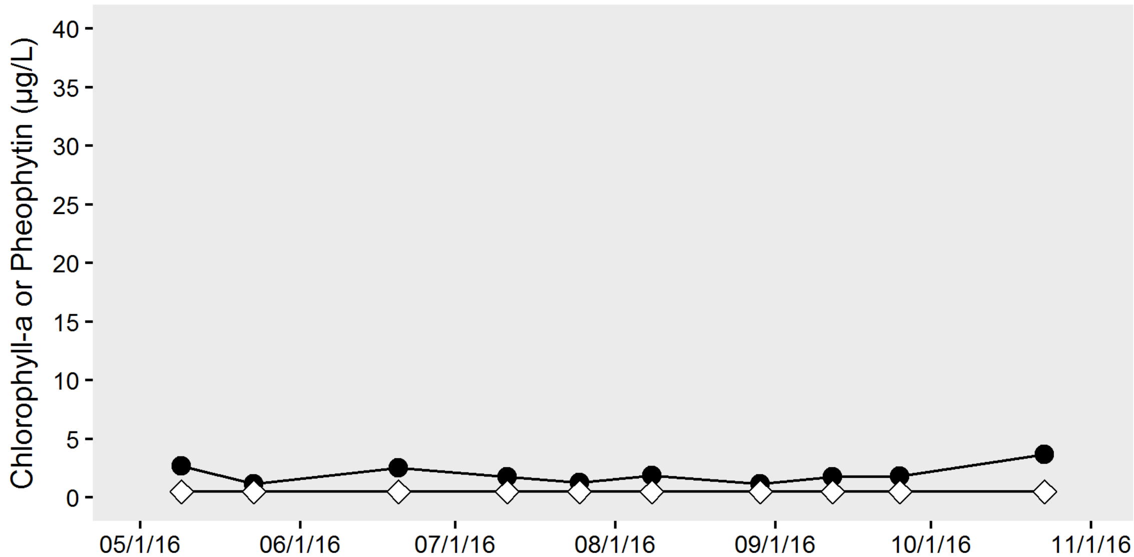

Figure 7. Lake Lucenre chlorophyll-*a* (black circles) and pheophytin (white diamonds) concentrations.

Concentrations of chlorophyll-*a* in Lake Lucerne were low throughout the 2016 sampling season. Of the small lakes monitored in King County, Lake Lucerne had one of the lowest mean chlorophyll-*a* concentrations in 2016, which is in line with the high degree of water clarity (deep Secchi depths) observed in the lake. Pheophytin remained below or near detection limits all summer, indicating that the samples were fresh and stored properly.

3.7 Trophic State Index

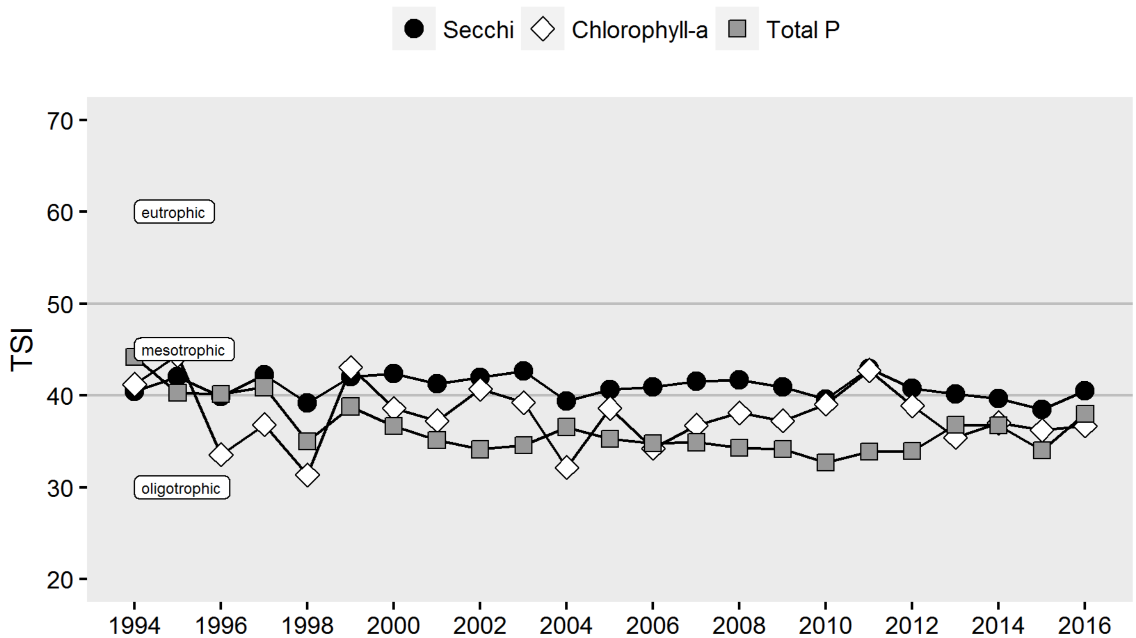

Figure 8. Lake Lucerne average May-October Trophic State Indices.

In 2016, all three average TSI values for Lake Lucerne remained close together and in the upper oligotrophic or low mesotrophic range. The Secchi TSI has generally been higher than the other two TSI values, especially total phosphorus. Water clarity in Lake Lucerne has tended to be lower than Carlson's TSI model would predict.

TSI values showed some fluctuation from year to year, with no discernable trend over time. (Note that total phosphorus data prior to 1998 are excluded from this trend analysis, since total phosphorus analytical methods changed between 1997 and 1998.) Continued monitoring of Lake Lucerne will help track any changes that occur in the future.

3.8 Water Column Profile

In May, water was collected at the mid-lake sampling station from three depths in a water-column profile: 1 m, the middle depth of the water column, and 1 m from the lake bottom. The second profile, scheduled for August, was not collected in 2016.

Table 3. Lake Lucerne water column profile data.

Date	Secchi (m)	Depth (m)	Temp (°C)	Chlor (µg/L)	Pheo (µg/L)	TN (µg/L)	$NO_{2/3}$ (µg/L)	NH_3 (µg/L)	TP (µg/L)	OPO_4 (µg/L)	Alk (mg/L)	UV254
5/23/2016	5.2	1.0	17.0	1.2	(0.5)	403	45.0	27.1	8.3	(0.5)	28.1	0.074
		5.0	13.0	10.6	1.6	486			16.9			
		9.0	7.0			573	17.0	159.0	47.0	(0.5)		

Note: Parameter abbreviations are: chlorophyll-*a* (Chlor.), pheophytin (Pheo.), total nitrogen (TN), nitrate/nitrite ($NO_{2/3}$), ammonia (NH_3), total phosphorus (TP), orthophosphate (OPO_4), and total alkalinity (Alk). UV254 is measured in absorption units. Dashes indicate parameters that were not analyzed for a given sample. Values below the method detection limit (MDL) are enclosed in parentheses and have the value of the MDL substituted.

Temperature data indicate that thermal stratification (layering of warm shallow water over cooler deeper water) was present. The deeper water sample contained higher concentrations of nitrogen and phosphorus than the surface waters. This indicates that the hypolimnion (the deeper, cooler layer of water) was low in oxygen during the summer. Higher ammonia concentrations in the deep water samples may also indicate anoxia. However, orthophosphate (OPO_4) levels were not elevated at depth, indicating little release of phosphorus from the sediments into the lake.

Chlorophyll-*a* profile data indicate that algae were present in the water column, but at higher concentrations in mid-depth waters. This suggests that enough light was reaching deeper waters to stimulate algal growth, or that algal species able to adapt to lower light levels were able to take advantage of higher nutrient concentrations. These chlorophyll-*a* concentrations were fairly low, suggesting that the lake did not support an abundance of phytoplankton and had only moderate primary productivity.

UV254 absorption measurements indicate that the water in Lake Lucerne was very lightly colored by dissolved organic substances. Total alkalinity was moderately low, indicating that the water was only lightly buffered against changes in pH, and thus was potentially sensitive to acidification.

4.0 PIPE LAKE RESULTS

4.1 Data Summary

Table 3 summarizes data from 2016, giving the minimum, mean (average) and maximum values measured for each parameter for the May-October sampling season.

Table 3. Pipe Lake May-October summary statistics.

	Parameter	Minimum	Mean	Maximum
2016 May-Oct.	Secchi depth	4.8	6.3	7.8
	Temperature	15.0	20.8	24.0
	Chlorophyll-*a*	1.1	1.8	2.4
	Total Nitrogen	257.0	356.6	595.0
	Total Phosphorus	6.9	11.7	17.7
	N:P ratio	20.7	31.6	56.1

Note: Secchi depth in m. Temperature in degrees Celsius. Chlorophyll-*a*, pheophytin, total nitrogen, and total phosphorus in µg/L.

4.2 Secchi Depth

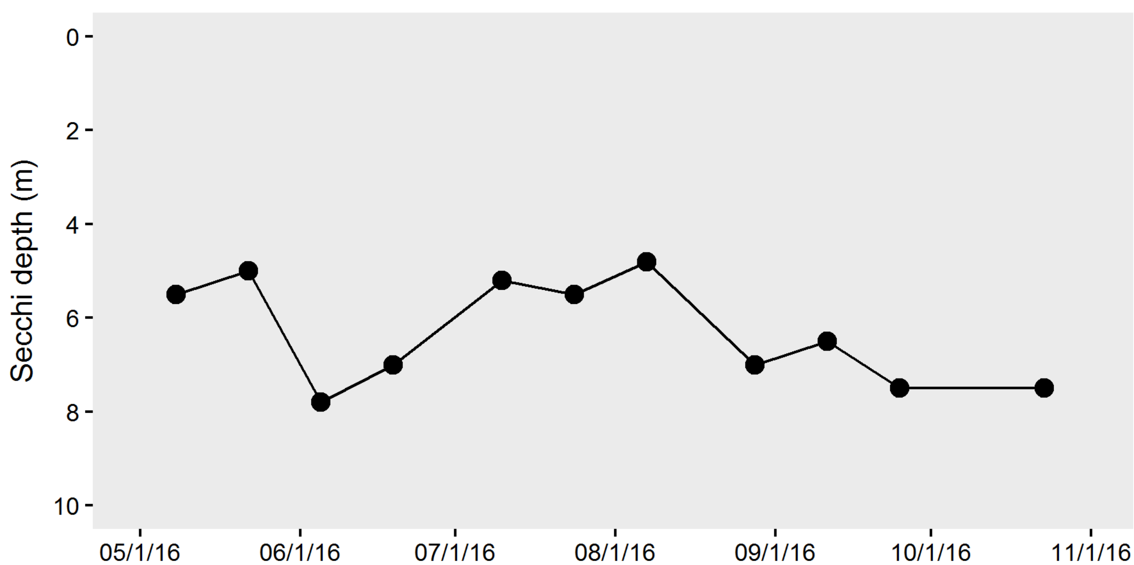

Figure 9. Pipe Lake Secchi depth. Note the inverted Y-axis.

In 2016, there was no clear seasonal trend in Secchi-depth readings, which were moderately deep throughout the May-October sampling season.

4.3 Water Temperature

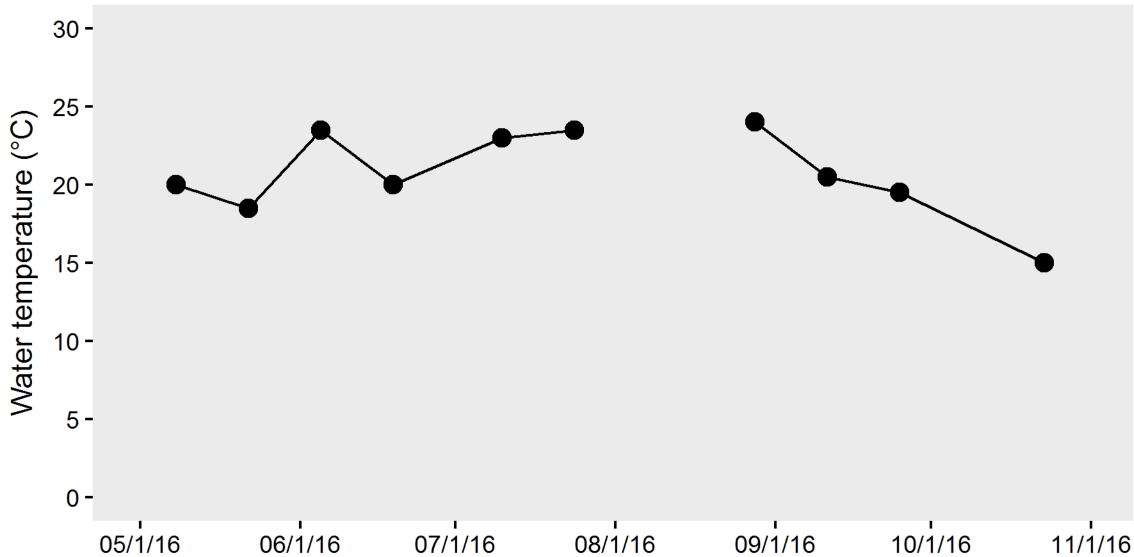

Figure 10. Pipe Lake water temperature at 1 m.

Lake temperatures in 2016 followed a typical pattern for small lakes in the region, with temperatures warming through the spring, reaching a summer maximum, and cooling by late September.

Average May-October water temperature in 2016 was lower than the previous few years. Overall, there is a slight but statistically discernable increasing trend in the long-term monitoring data ($p=0.001$, $R^2=0.38$), with an average increase of 1.3°C per decade.

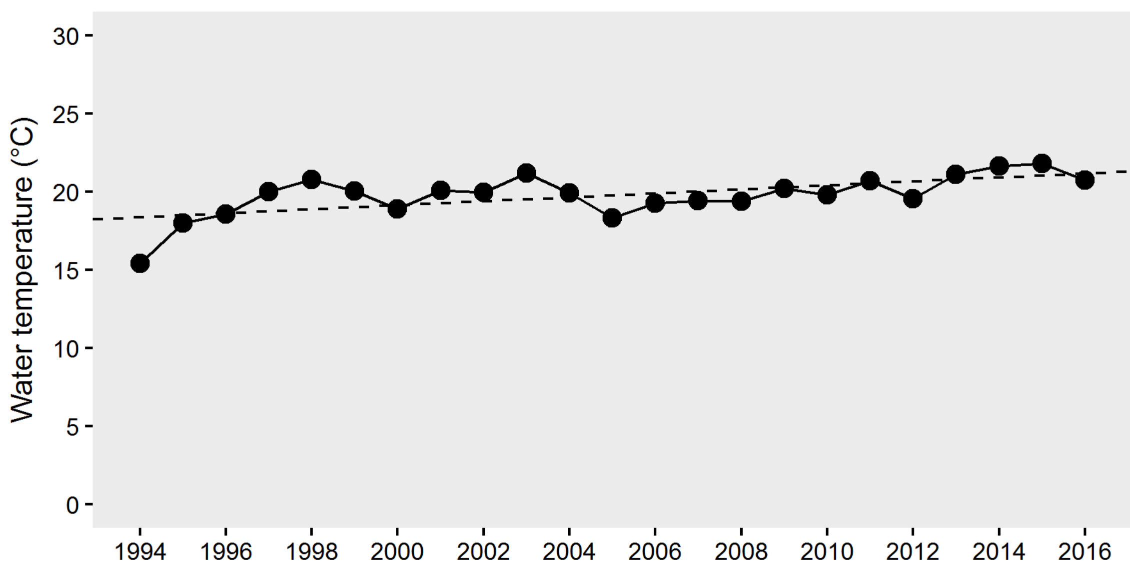

Figure 11. Pipe Lake average May-October water temperature at 1 m. Dashed line indicates long-term trend.

4.4 Total Phosphorus and Total Nitrogen

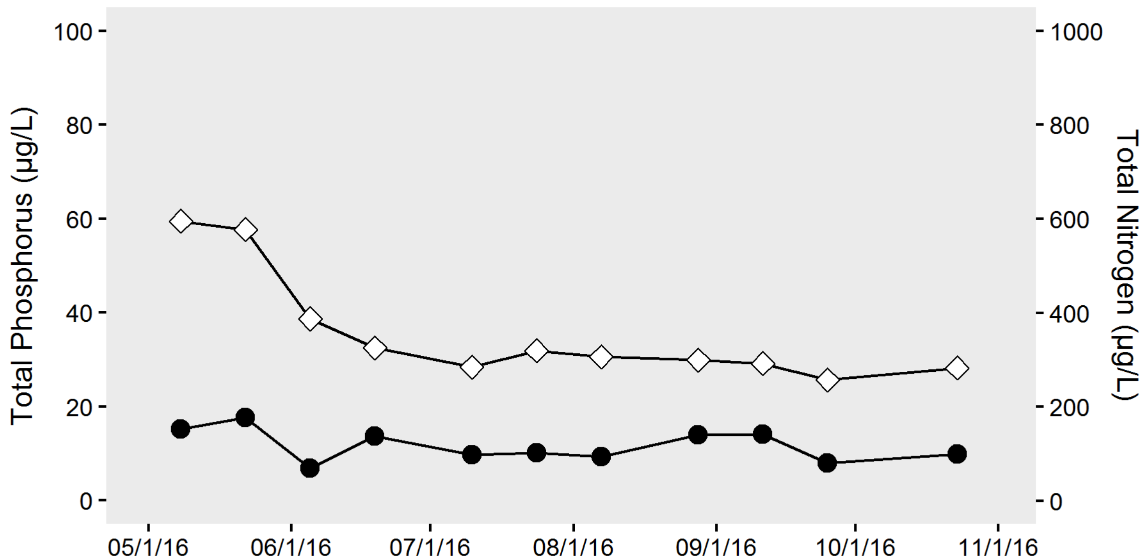

Figure 12. Pipe Lake total phosphorus (black circles) and total nitrogen (white diamonds) concentrations in µg/L.

Total nitrogen concentrations were highest in the spring, and were lower and relatively stable throughout the summer and fall. Total phosphorus concentrations exhibited no clear seasonal pattern.

4.5 Nutrient Ratios

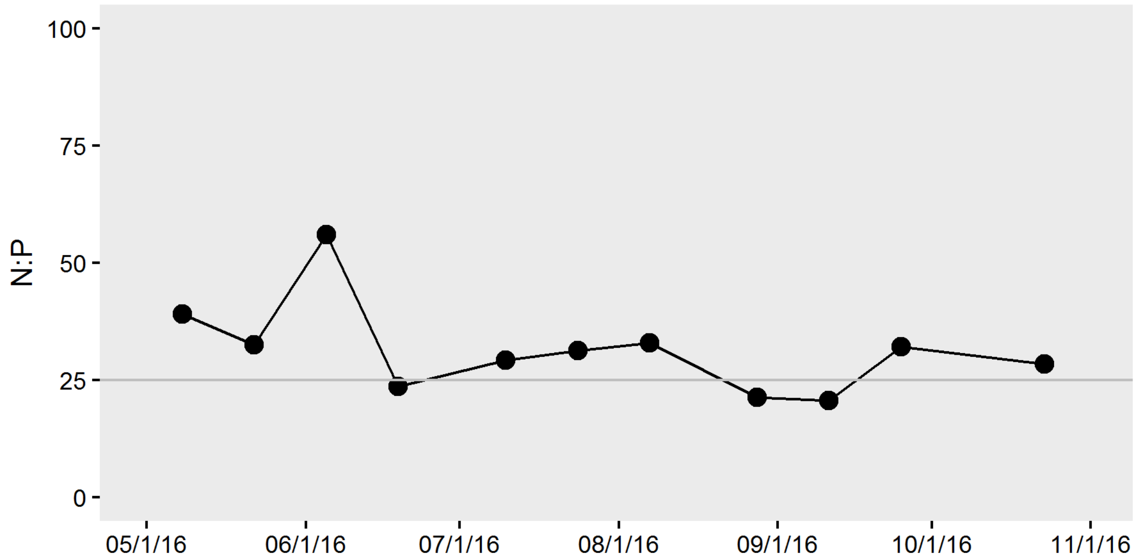

Figure 13. Pipe Lake N:P ratios. N:P ratios at or below 25 (solid line) indicate possible nitrogen limitation.

The ratio of total nitrogen to total phosphorus (N:P ratio) in Pipe Lake was mostly above 25, except for a few sampling dates. There was also a peak in the N:P ratio in early June, driven by a low total phosphorus concentration. While phosphorus was most often the limiting nutrient in the lake, the dates with N:P near or below 25 indicated times of possible nitrogen co-limitation.

The 2016 average N:P ratio was the lowest of any year on record for Pipe Lake (and was also the lowest on record for Lake Lucerne). Long-term monitoring data suggest that this was due to year-to-year variability, rather than any long-term trend.

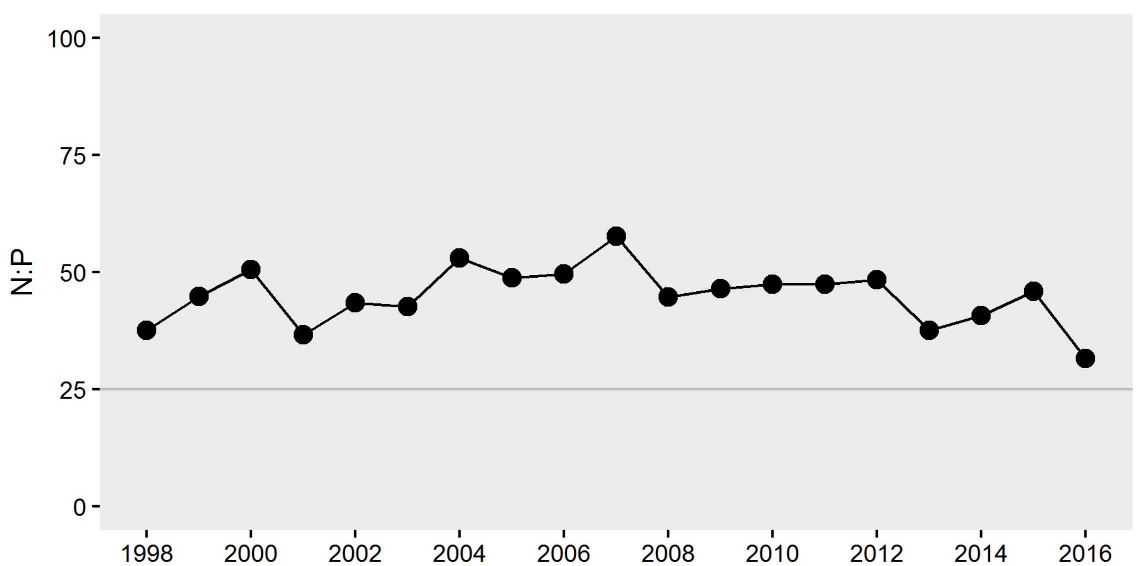

Figure 14. Pipe Lake average May-October N:P ratios.

4.6 Chlorophyll-*a*

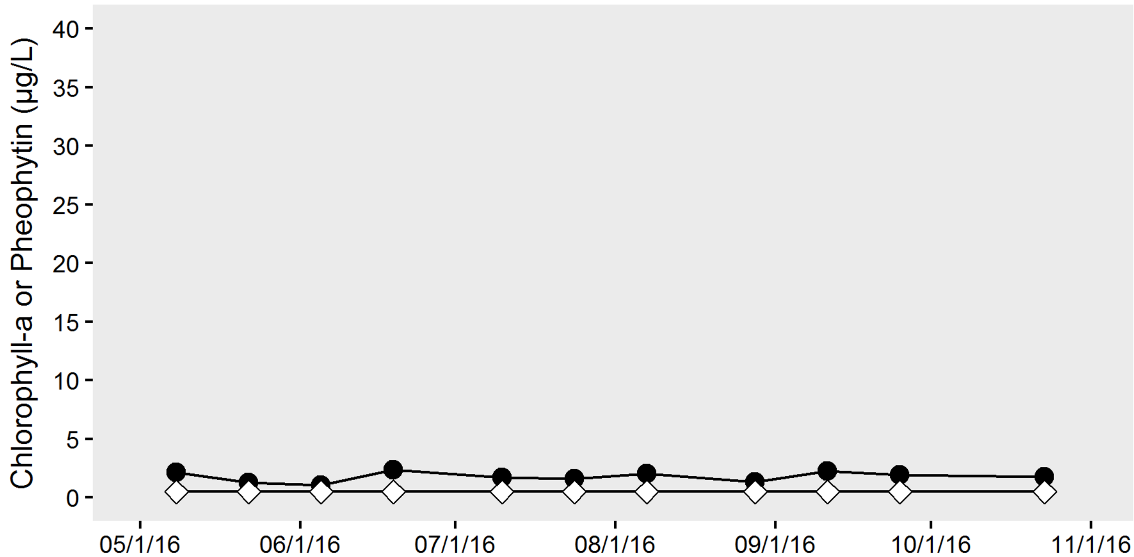

Figure 15. Pipe Lake chlorophyll-*a* (black circles) and pheophytin (white diamonds) concentrations.

Concentrations of chlorophyll-*a* in Pipe Lake remained low throughout the 2016 sample season. Of the small lakes monitored in King County in 2016, Pipe Lake had one of the lowest mean chlorophyll-*a* concentrations, which is in line with the high degree of water clarity observed in the lake. Pheophytin remained below or near detection limits all summer, indicating that the samples were fresh and stored properly.

4.7 Trophic State Index

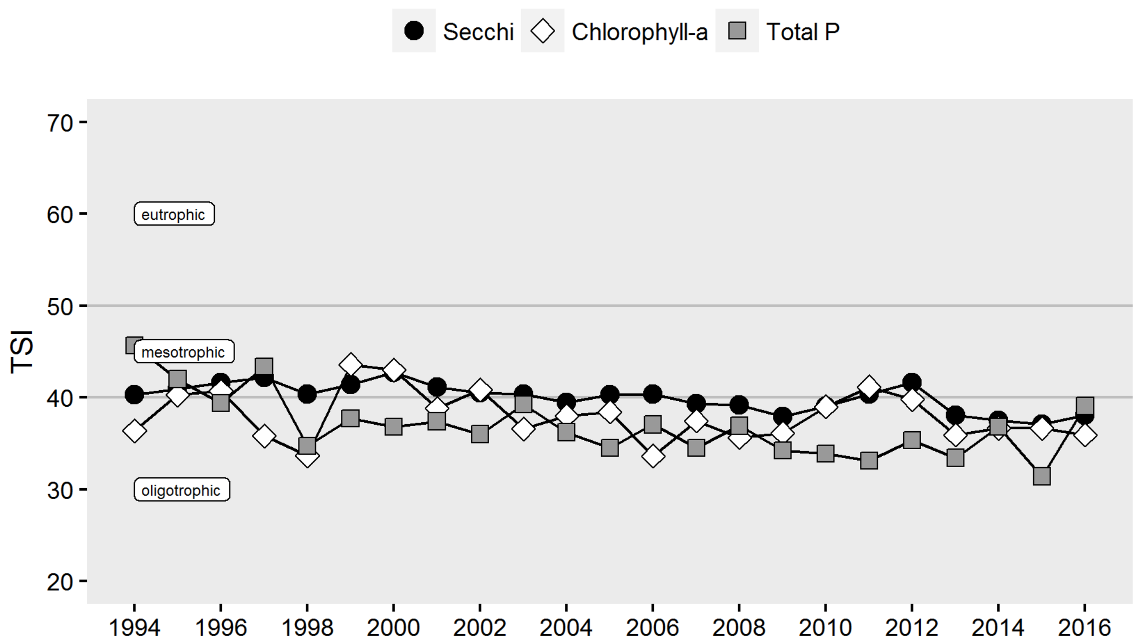

Figure 16. Pipe Lake average May-October Trophic State Indices.

In 2016, all three average TSI values for Pipe Lake were close together and within the oligotrophic range. The total-phosphorus TSI had been markedly lower than the other two in 2015, but was slightly higher than the others in 2016. In 2015, there was more algal biomass (and chlorophyll-*a*) in Pipe Lake than Carlson's TSI model would predict from phosphorus concentrations. In 2016, by contrast, there was slightly less algal biomass than the model would predict.

Individual TSI values have fluctuated up and down over time, with no overall trends in the long-term monitoring data. Continued monitoring of Pipe Lake will help track any changes that occur in the future.

4.8 Water Column Profile

In May and August, water was collected at the mid-lake sampling station from three depths in a water-column profile: 1 m, the middle depth of the water column, and 1 m from the lake bottom.

Table 4. Pipe Lake water column profile data.

Date	Secchi (m)	Depth (m)	Temp (°C)	Chlor (µg/L)	Pheo (µg/L)	TN (µg/L)	$NO_{2/3}$ (µg/L)	NH_3 (µg/L)	TP (µg/L)	OPO_4 (µg/L)	Alk (mg/L)	UV254
5/22/2016	5.0	1.0	18.5	1.3	(0.5)	577	129.0	29.9	17.7	2.2	27.7	0.070
		10.0	13.0	6.6	(0.5)	692	-	-	10.7	-	-	-
		19.0	7.0	-	-	741	284.0	188.0	76.6	20.4	-	-
8/28/2016	7.0	1.0	24.0	1.3	(0.5)	299	(5.0)	4.3	14.0	(0.5)	29.4	0.059
		10.0	9.0	3.9	3.7	674	-	-	29.9	-	-	-
		19.0	7.5	-	-	1160	10.0	910.0	342.0	90.7	-	-

Note: Parameter abbreviations are: chlorophyll-*a* (Chlor.), pheophytin (Pheo.), total nitrogen (TN), nitrate/nitrite ($NO_{2/3}$), ammonia (NH_3), total phosphorus (TP), orthophosphate (OPO_4), and total alkalinity (Alk). UV254 is measured in absorption units. Dashes indicate parameters that were not analyzed for a given sample. Values below the method detection limit (MDL) are enclosed in parentheses and have the value of the MDL substituted.

Temperature data indicate that thermal stratification (layering of warm shallow water over cooler deeper water) was present in May and August. The deeper water samples contained higher concentrations of nitrogen and phosphorus than the surface waters. This indicates that the hypolimnion (the deeper, cooler layer of water) was low in oxygen during the summer. Anoxia (lack of oxygen) facilitates the release of phosphorus from bottom sediments into the water, resulting in higher orthophosphate concentrations. Higher ammonia concentrations in the deep water samples may also indicate anoxia.

Chlorophyll-*a* profile data indicate that algae were present in the water column, with higher concentrations in mid-depth waters. This suggests that enough light was reaching deeper waters to stimulate algal growth, or that algal species able to adapt to lower light levels were able to take advantage of higher nutrient concentrations. However, sample dates had moderately low chlorophyll concentrations overall, suggesting that the lake did not support an abundance of phytoplankton and had only moderate primary productivity.

The low UV254 absorption measurements in Pipe Lake indicate that the lake was fairly clear, with little coloration from dissolved organic substances. Total alkalinity values were fairly low, indicating that the lake water was only lightly buffered against changes in pH, and thus was potentially sensitive to acidification.

5.0 LAKE WILDERNESS RESULTS

5.1 Data Summary

Table 5 summarizes data from 2016, giving the minimum, mean (average) and maximum values measured for each parameter. This includes annual summary values for Secchi and temperature, which were measured year-round as part of Level I monitoring, and May-October summary values for all parameters.

Table 5. Lake Wilderness annual and May-October summary statistics.

	Parameter	Minimum	Mean	Maximum
2016 Annual	Secchi depth	2.5	5.2	8.3
	Temperature	4	14.2	24
2016 May-Oct.	Secchi depth	3.8	5.7	8.3
	Temperature	14	19.8	24
	Chlorophyll-*a*	1.2	4.2	10.1
	Total Nitrogen	349	560.1	973
	Total Phosphorus	11.6	19.9	59.7
	N:P ratio	9.9	33.9	66.2

Note: Secchi depth in m. Temperature in degrees Celsius. Chlorophyll-*a*, pheophytin, total nitrogen, and total phosphorus in µg/L.

5.2 Lake Level and Precipitation

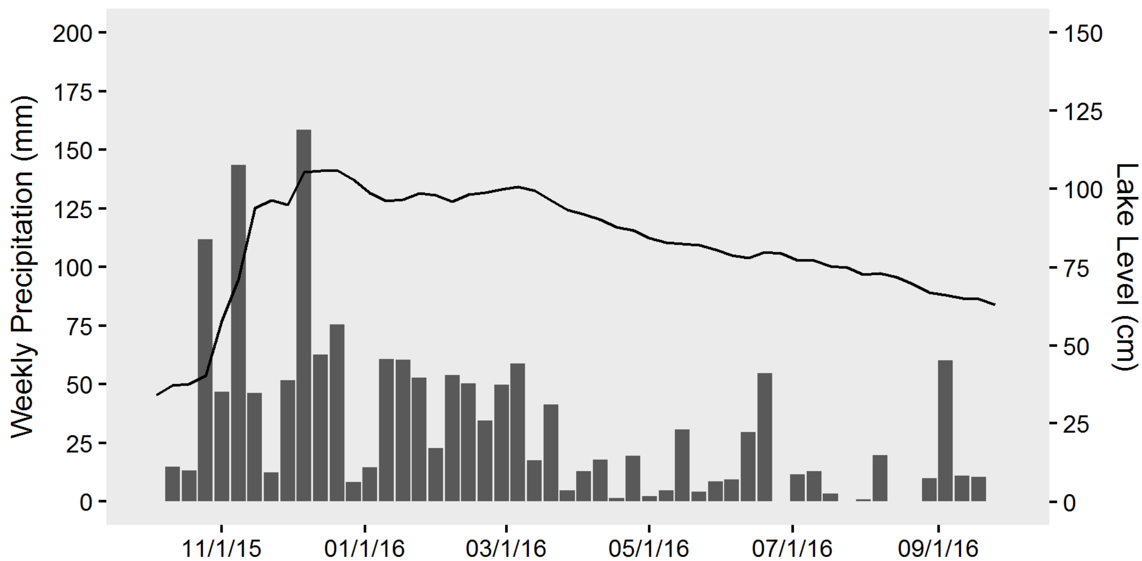

Figure 17. Lake Wilderness weekly mean lake level (line) and total weekly precipitation (bars).

Lake level rose sharply in fall 2015, remained high through the winter, and declined gradually through spring and summer 2016.

5.3 Secchi Depth

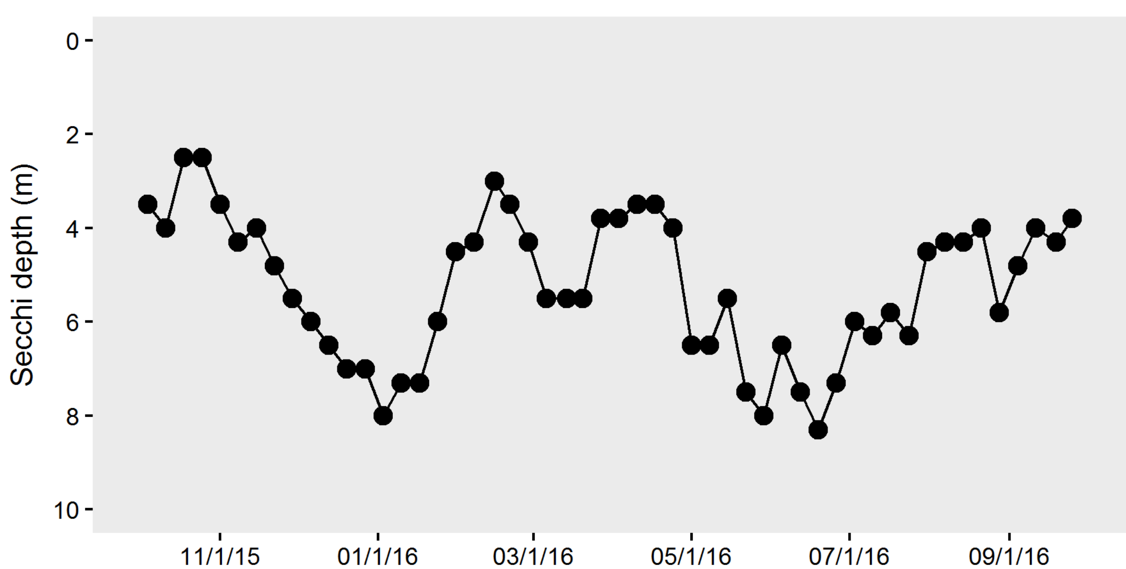

Figure 18. Lake Wilderness Secchi depth. Note the inverted Y-axis.

Secchi depth in Lake Wilderness varied considerably throughout the year, and tended to be shallower during spring and fall, likely due to algal blooms.

5.4 Water Temperature

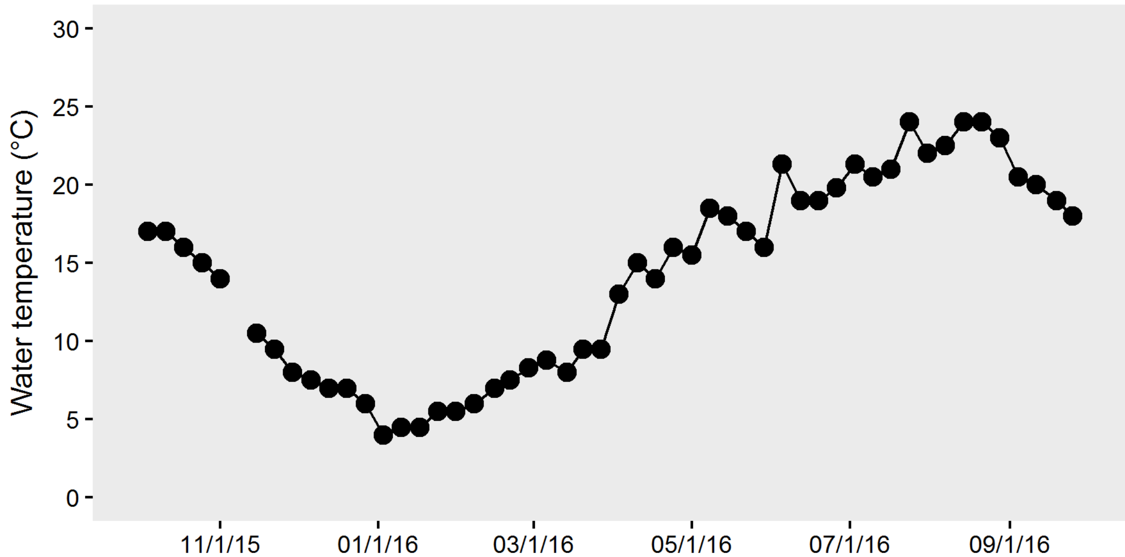

Figure 19. Lake Wilderness water temperature at 1 m.

Lake temperatures in 2016 followed a typical pattern for small lakes in the region, with cooler temperatures in the winter and spring, maximum temperatures occurring in late summer, and temperatures cooling by late September.

Average May-October water temperatures in 2016 were similar to the previous few years. Overall, there is no temperature trend in the long-term monitoring data.

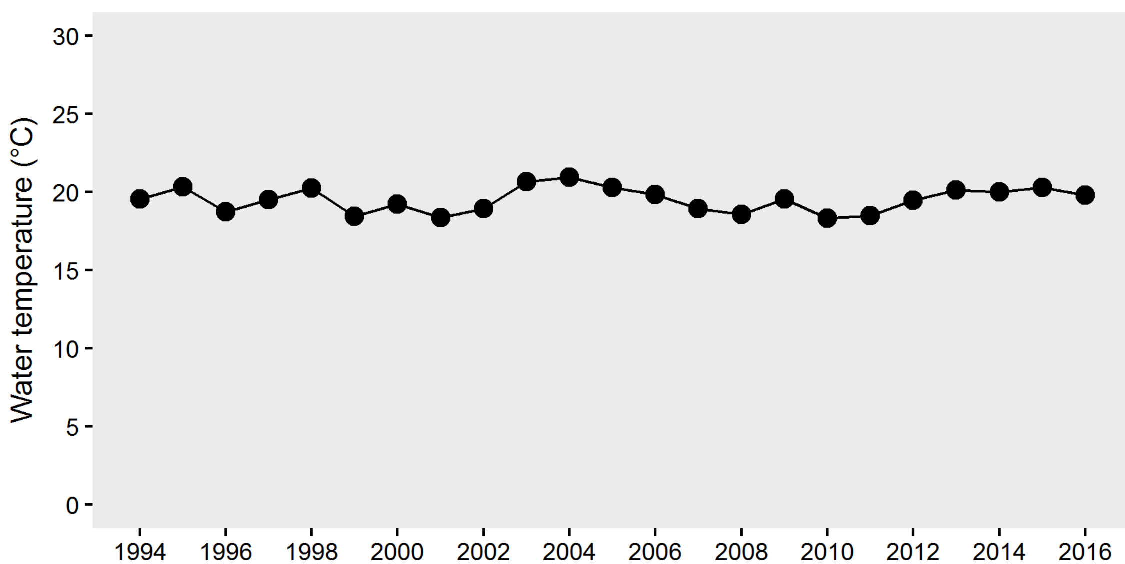

Figure 20. Lake Wilderness average May-October water temperature at 1 m

5.5 Total Phosphorus and Total Nitrogen

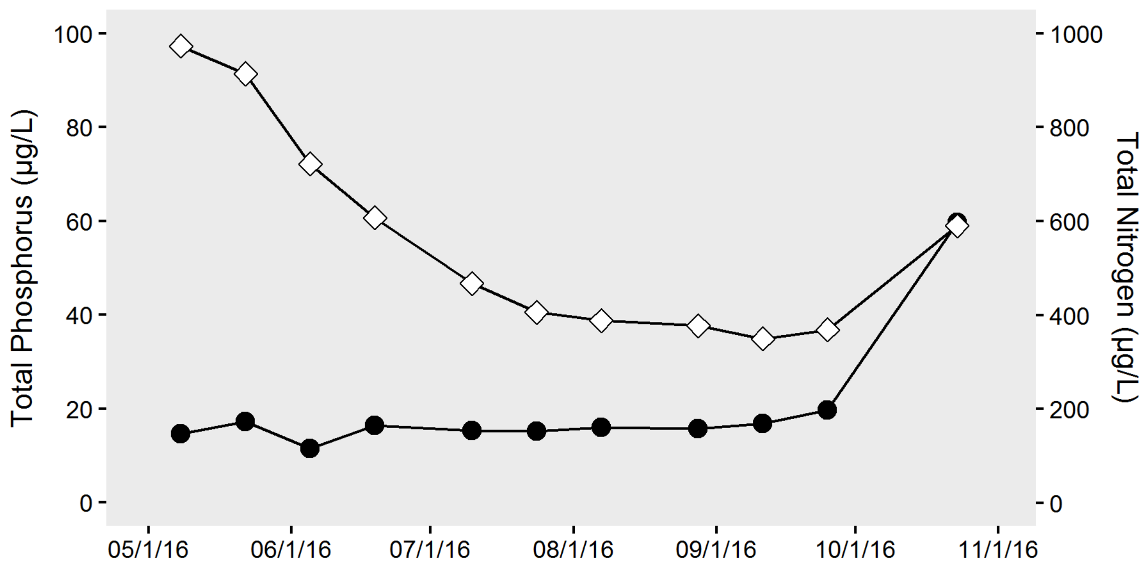

Figure 21. Lake Wilderness total phosphorus (black circles) and total nitrogen (white diamonds) concentrations in µg/L.

Total phosphorus concentrations remained fairly stable from May through September, while total nitrogen concentrations decreased substantially during that period. Both nitrogen and phosphorus concentrations increased sharply in October, similar to past years.

Long-term monitoring data show a statistically discernable increasing trend for total nitrogen concentrations ($p=0.01$, $R^2=0.28$), with an average increase of 50 µg/L per decade. In contrast, total phosphorus concentrations appear to have decreased over time, though this trend is not statistically discernable.

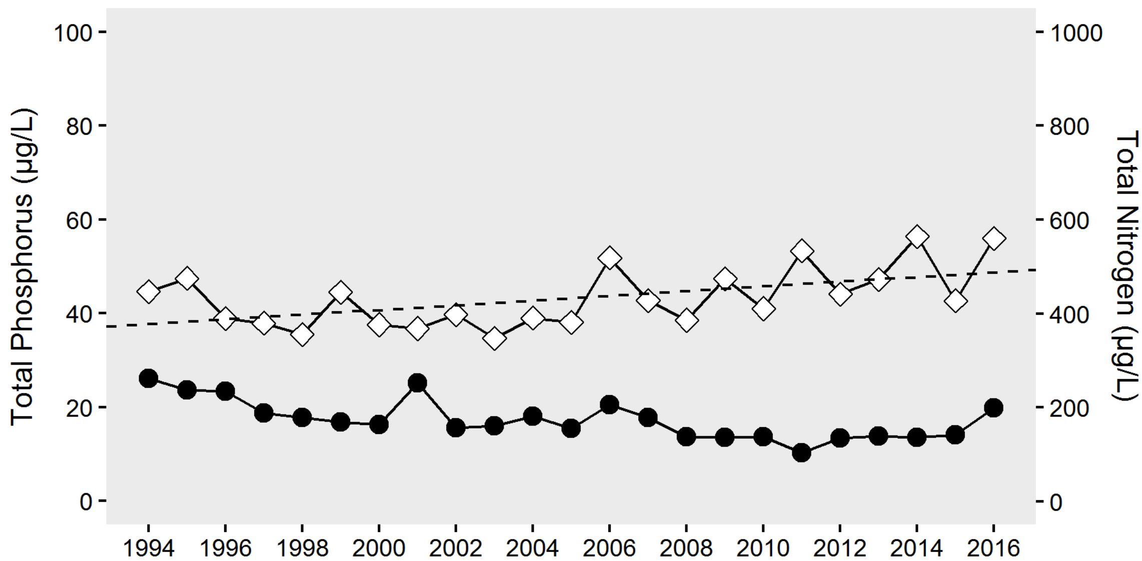

Figure 22. Lake Wilderness average May-October total phosphorus (black circles) and total nitrogen (white diamonds) concentrations in µg/L. Dashed line indicates the long-term trend in total nitrogen concentrations.

5.6 Nutrient Ratios

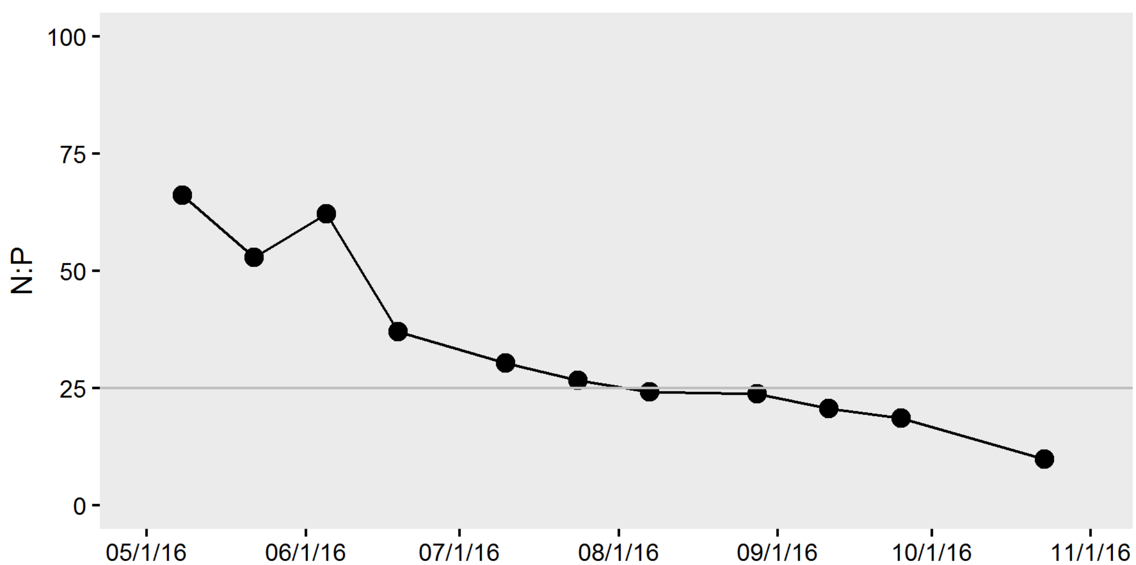

Figure 23. Lake Wilderness N:P ratios. N:P ratios at or below 25 (solid line) indicate possible nitrogen limitation.

The ratio of total nitrogen to total phosphorus (N:P ratio) decreased throughout the sampling period, driven primarily by decreases in the total nitrogen concentration. Phosphorus was the limiting nutrient in the first half of the monitoring period, when N:P ratios were above 25. From early August onwards, nitrogen and phosphorus were likely co-limiting algal productivity, creating nutrient conditions favorable for cyanobacteria to dominate the algal community.

The 2016 average May-October N:P ratio declined slightly from 2015. However, the long-term monitoring data still shows a clear increasing trend ($p=0.0004$, $R^2=0.52$), with an average increase of 13 per decade.

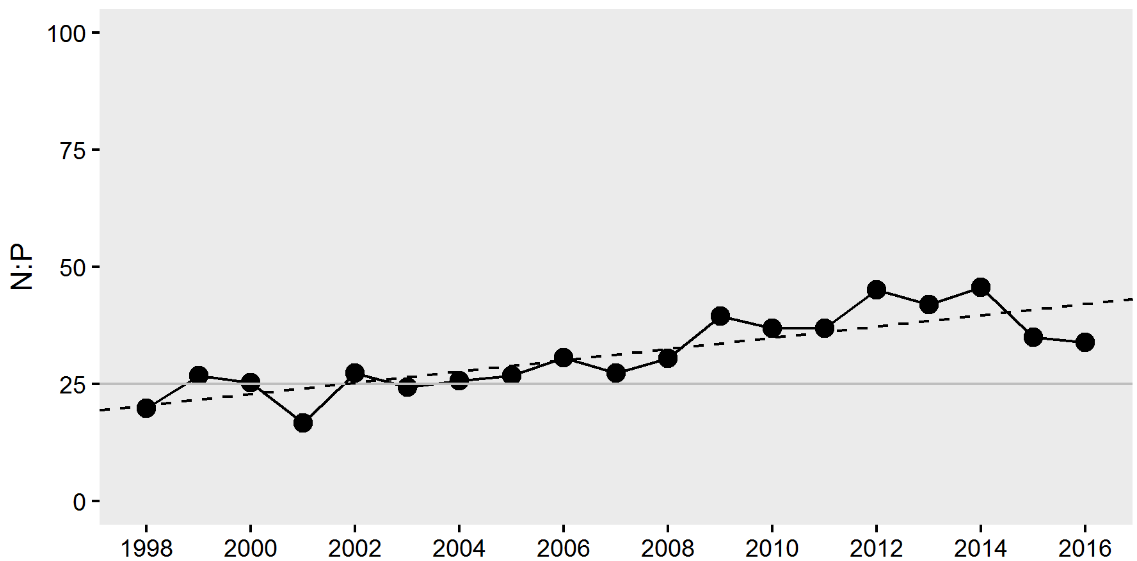

Figure 24. Lake Wilderness average May-October N:P ratios. Dashed line indicates long-term trend.

5.7 Chlorophyll-*a*

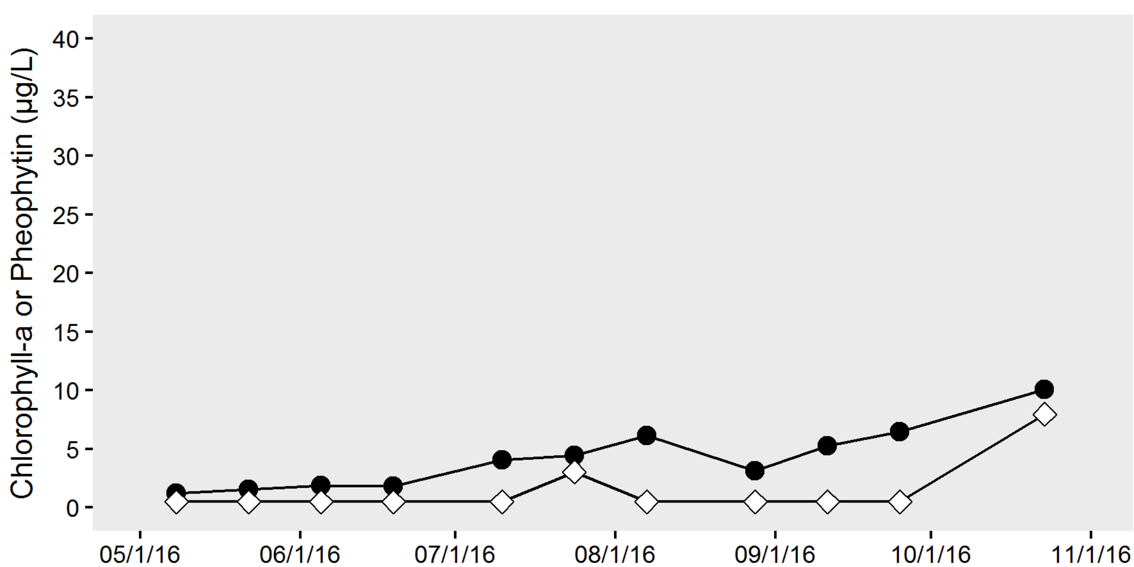

Figure 25. Lake Wilderness chlorophyll-*a* (black circles) and pheophytin (white diamonds) concentrations.

Concentrations of chlorophyll-*a* in Lake Wilderness rose gradually from low values in May. Pheophytin remained below or near detection limits all summer, indicating that the samples were fresh and stored properly.

5.8 Trophic State Index

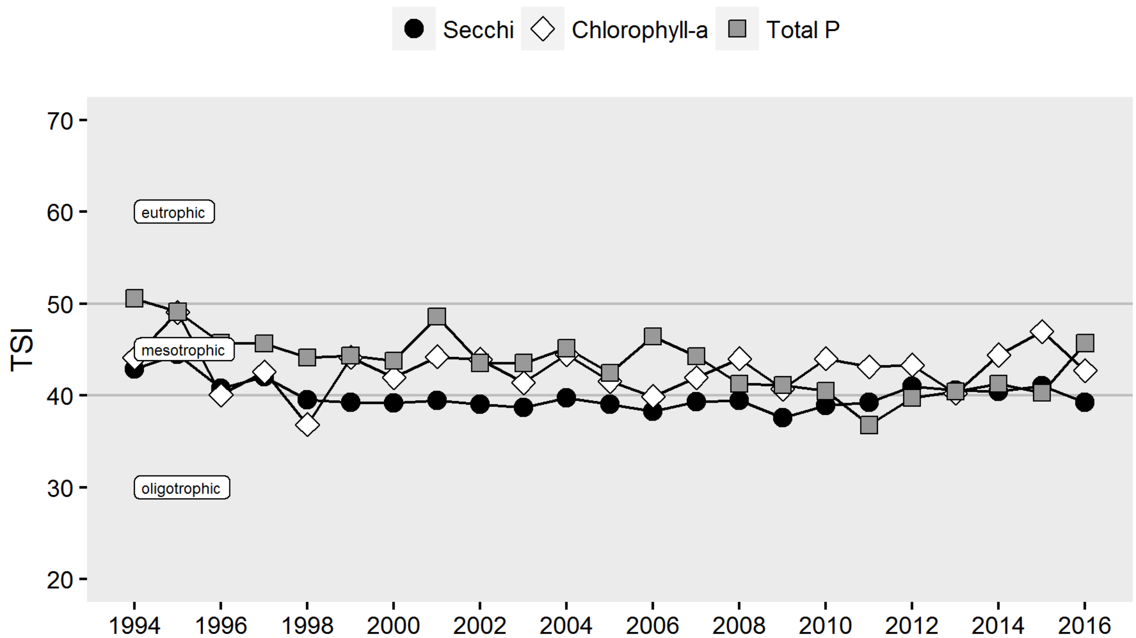

Figure 26. Lake Wilderness average May-October Trophic State Indices.

In 2016, average TSI values were in the mesotrophic or mesotrophic-oligotrophic range. Similar to Pipe Lake, the total-phosphorus TSI value rose above the other two in 2016. The algal biomass (and chlorophyll-*a*) in Pipe Lake was lower than Carlson's TSI model would predict.

The total phosphorus TSI has decreased over time ($p=0.02$, $R^2=0.29$), with an average decrease of 2.7 per decade. (Note that total phosphorus data prior to 1998 are excluded from this trend analysis, since total phosphorus analytical methods changed between 1997 and 1998.) Continued monitoring of Lake Wilderness will help track any changes that occur in the future.

5.9 Water Column Profile

In May and August, water was collected at the mid-lake sampling station from three depths in a water-column profile: 1 m, the middle depth of the water column, and 1 m from the lake bottom.

Table 6. Lake Wilderness water column profile data, 2016.

Date	Secchi (m)	Depth (m)	Temp (°C)	Chlor (µg/L)	Pheo (µg/L)	TN (µg/L)	$NO_{2/3}$ (µg/L)	NH_3 (µg/L)	TP (µg/L)	OPO_4 (µg/L)	Alk (mg/L)	UV254
5/22/2016	7.5	1.0	17.0	1.6	(0.5)	914	544.0	46.8	17.3	1.6	41.0	0.022
		4.0	16.5	1.2	(0.5)	847			13.1			
		8.5	10.5	27.6		703	140.0	126.0	102.0	14.8		
8/28/2016	5.8	1.0	23.0	3.1	(0.5)	377	(5.0)	9.2	15.8	1.6	44.0	0.031
		4.0	23.0	3.1	1.0	295			13.2			
		8.5	14.0	24.6	28.7	1540	15.0	516.0	217.0	9.7		

Note: Parameter abbreviations are: chlorophyll-*a* (Chlor.), pheophytin (Pheo.), total nitrogen (TN), nitrate/nitrite ($NO_{2/3}$), ammonia (NH_3), total phosphorus (TP), orthophosphate (OPO_4), and total alkalinity (Alk). UV254 is measured in absorption units. Dashes indicate parameters that were not analyzed for a given sample. Values below the method detection limit (MDL) are enclosed in parentheses and have the value of the MDL substituted.

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The low UV254 absorption measurements in Lake Wilderness indicate that the lake was fairly clear, with little coloration from dissolved organic substances. Total alkalinity values were moderately low, indicating that the lake water is only lightly buffered against changes in pH, and thus is potentially sensitive to acidification.

6.0 CONCLUSIONS AND RECOMMENDATIONS

Lake Lucerne and Pipe Lake continued to be categorized as oligotrophic, with moderately low algal productivity and good water quality. Lake Wilderness was categorized as mesotrophic, with higher algal productivity.

Average nitrogen to phosphorus (N:P) ratios were generally higher than 25 in Lake Lucerne, indicating that algal productivity was usually limited by phosphorus. The combination of low nutrient concentrations and phosphorus limitation created conditions that were unfavorable for cyanobacteria blooms. In Pipe Lake and Lake Wilderness, N:P ratios were below 25 for part of the sampling season, indicating that algal productivity was co-limited by both nitrogen and phosphorus. These nutrient conditions were more favorable for cyanobacteria to dominate the algal community.

Trend analyses of the long-term monitoring data found an increasing trend in the N:P ratio in Lake Wilderness, driven by both a decrease in total phosphorus concentrations as well as an increase in total nitrogen concentrations. In addition, the long-term data show that Pipe Lake water temperatures have been warming, with an average increase of 1.3°C per decade.

The monitoring conducted by volunteer stewards at these three lakes has built an invaluable long-term dataset for understanding water quality and lake health over time. Continued monitoring will help grow this dataset, increasing our understanding of how the lake reacts to environmental variability and human influences. The long-term dataset makes it possible to conduct statistically robust tests for trends, as well as to detect any potentially detrimental changes that may occur in the lake. In addition, long-term monitoring provides a solid scientific basis to guide lake management decisions by identifying emergent management needs and evaluating the effectiveness of management actions.